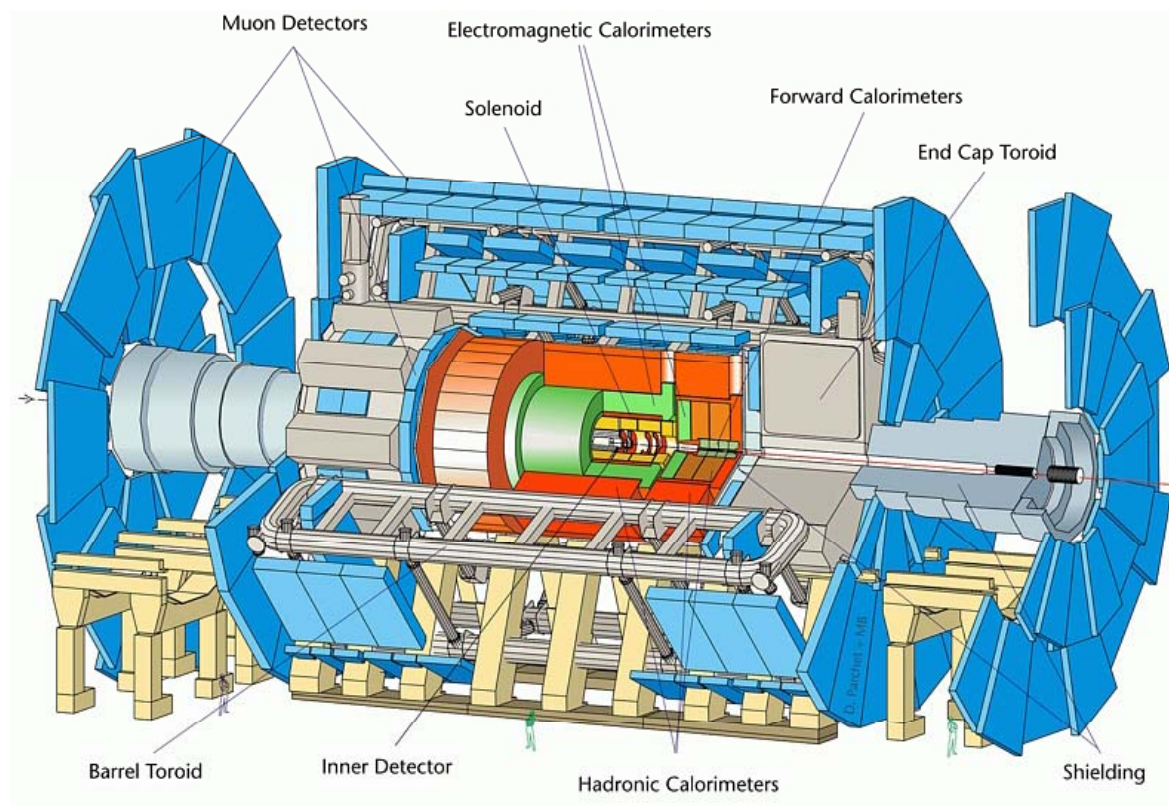
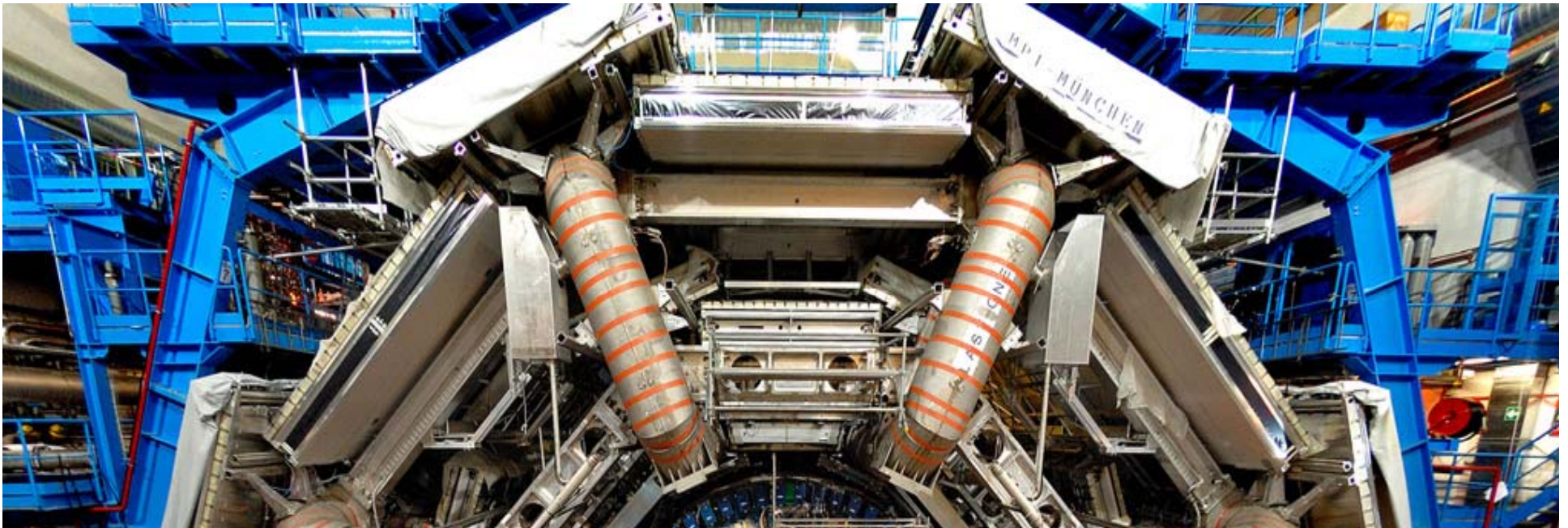




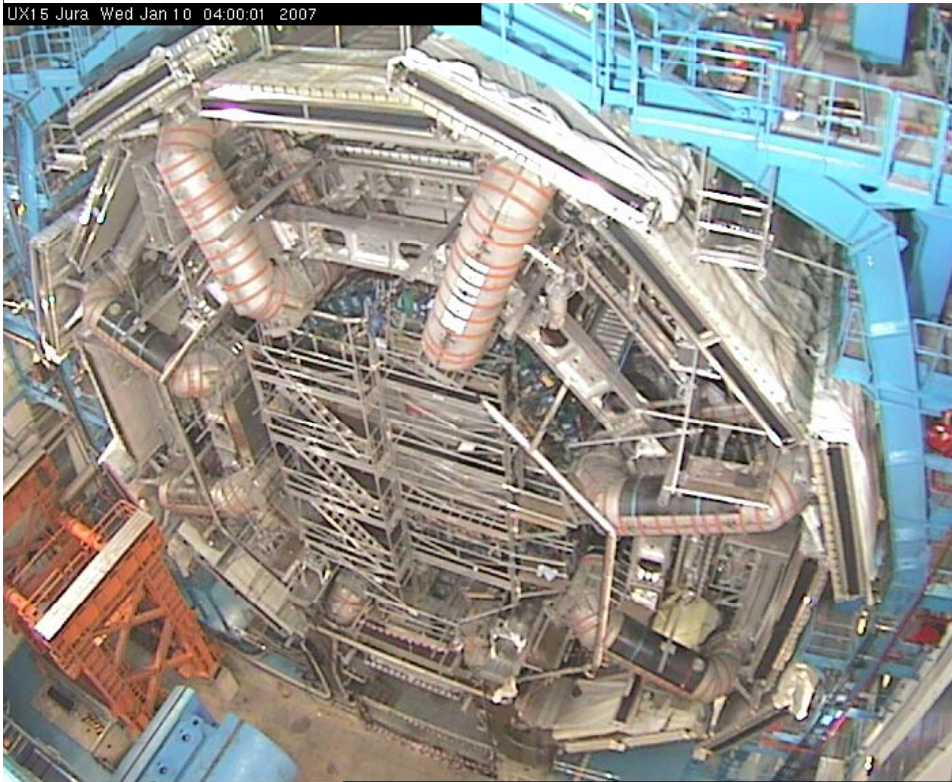
ATLAS Heavy Ion Physics



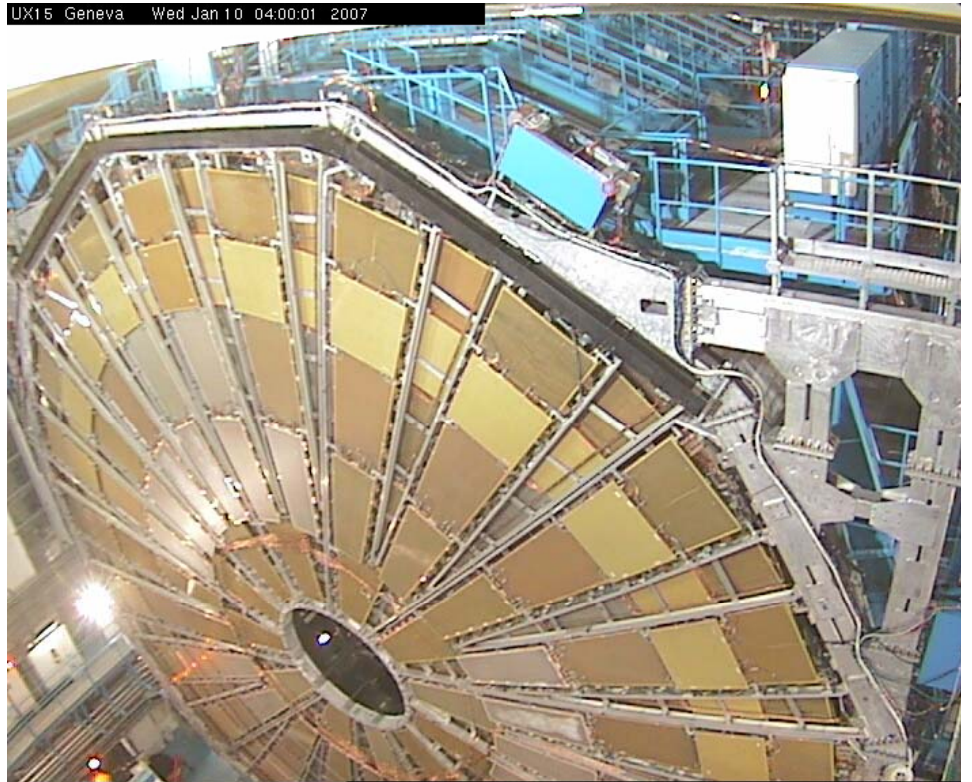
Andrzej Olszewski (INP PAN Kraków)
for the ATLAS Collaboration



UX15 Jura Wed Jan 10 04:00:01 2007



UX15 Geneva Wed Jan 10 04:00:01 2007





Heavy Ion Collisions at LHC

RHIC: Energy 200 GeV/n observations

- Strong quenching of high transverse momentum particles
- Near-Perfect liquid behavior of a collective motion in medium
- Collective motion of hadrons generated at parton level
- Parton saturation manifested in low multiplicity of final hadrons

Discovery of two new forms of QCD matter

- **sQGP** – strongly coupled Quark-Gluon Plasma
- **CGC** – a saturated gluon initial state (QGP-source)

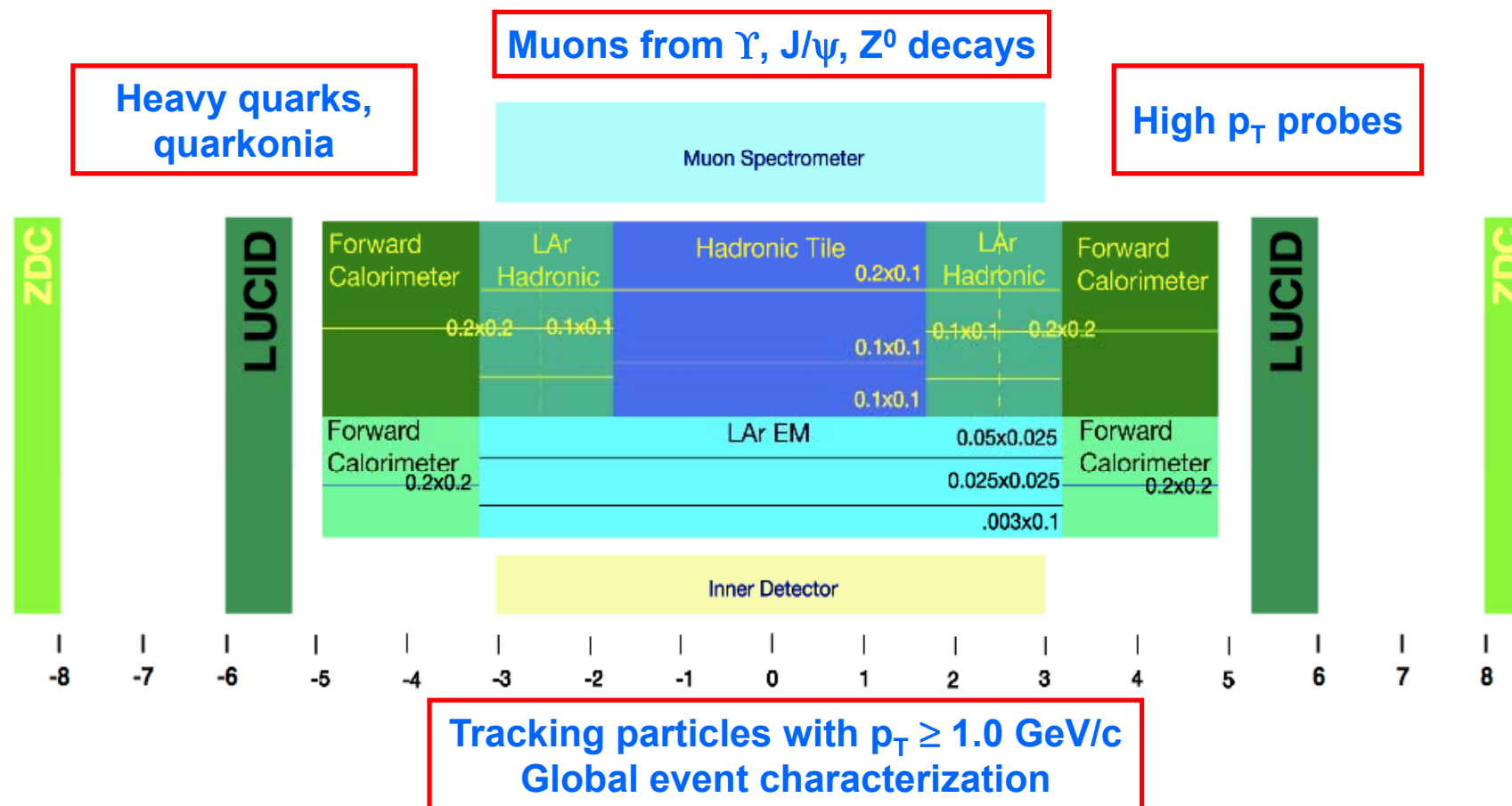
LHC: Energy 5.5 TeV/n opportunities

- Initial energy density ~ 5 times higher
- Lifetime of a quark-gluon plasma much longer
- Large rates of hard probes over a broad kinematical range

Era of quantitative experimental exploration of thermal QCD



ATLAS Acceptance



Unprecedented acceptance for A+A physics
both in p_T and rapidity, with full azimuthal coverage



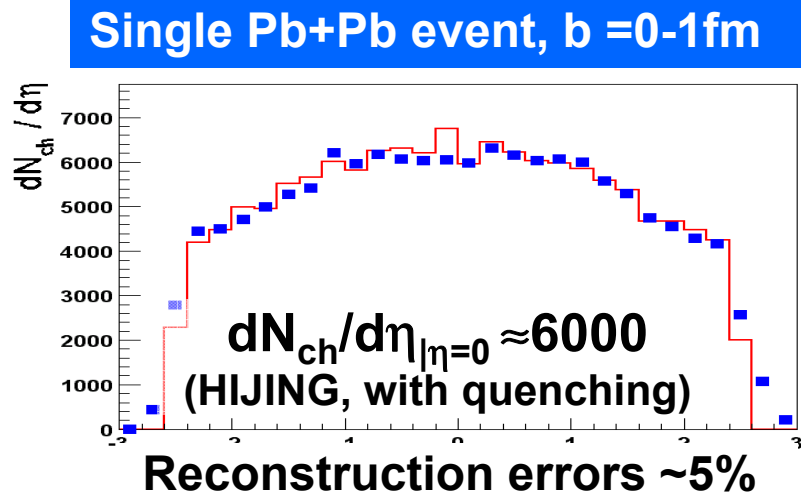
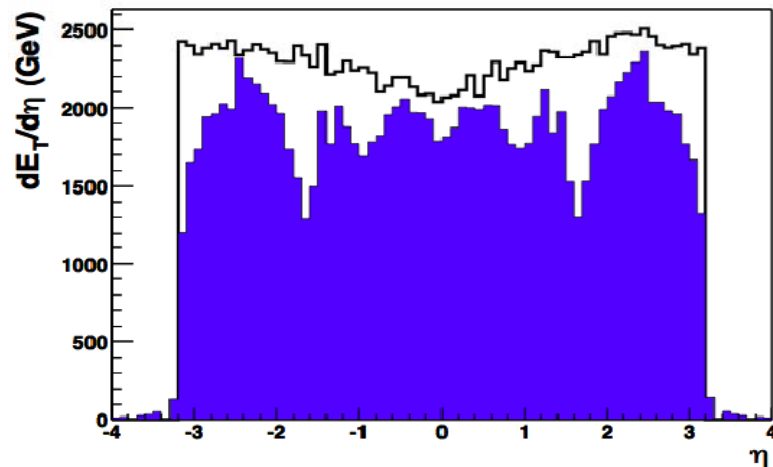
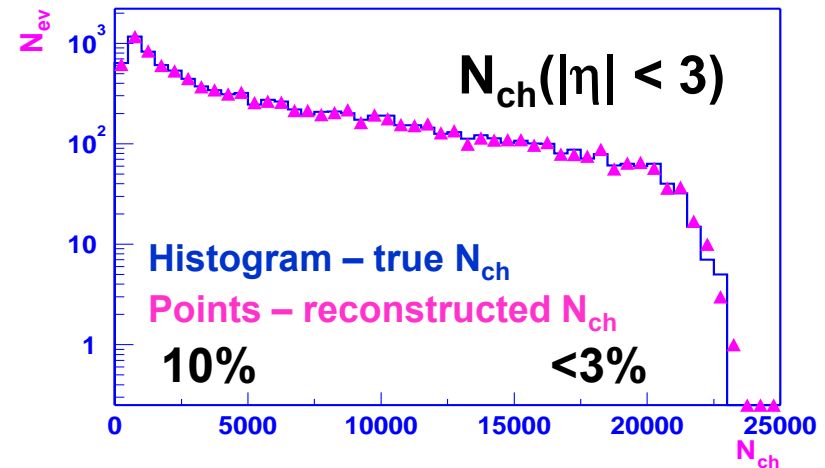
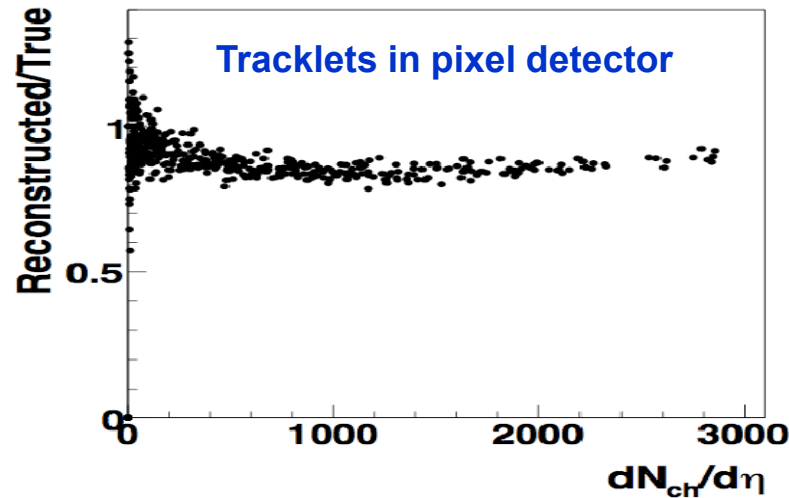
ATLAS Heavy Ion Program

- **Measure $dN_{ch}/d\eta$, $dE_T/d\eta$ (total+EM)**
 - Characterize gross properties of initial state
 - Test saturation predictions
- **Measure charged, inclusive γ , π^0 elliptic flow**
 - Probe early collective motion of (s/t/w)QGP
- **Measure jets, jet fragmentation, γ -Jet, di-jet, ...**
 - Precision tomography of QGP & its properties
 - Medium effects in jet quenching
- **Measure quarkonia production rates via $\mu^+\mu^-$ decays**
 - Probe Debye screening in medium
- **Study low x hard processes in p-p, p-A**
 - Study factorization violations, saturation



Global Event Characterization

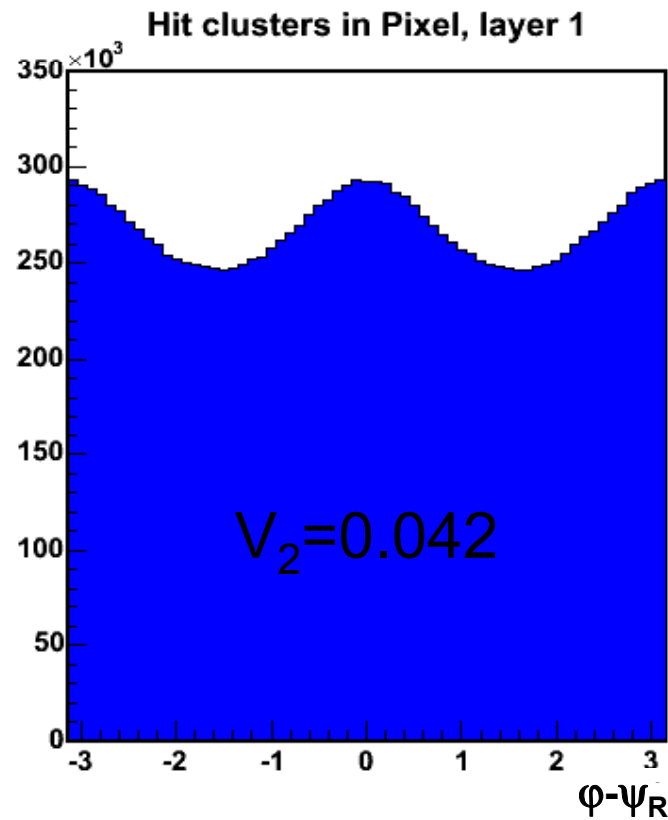
Day-one measurements: N_{ch} , $dN_{ch}/d\eta$, ΣE_T , $dE_T/d\eta$, b





Elliptic Flow

Generated $v_2 = 0.05$

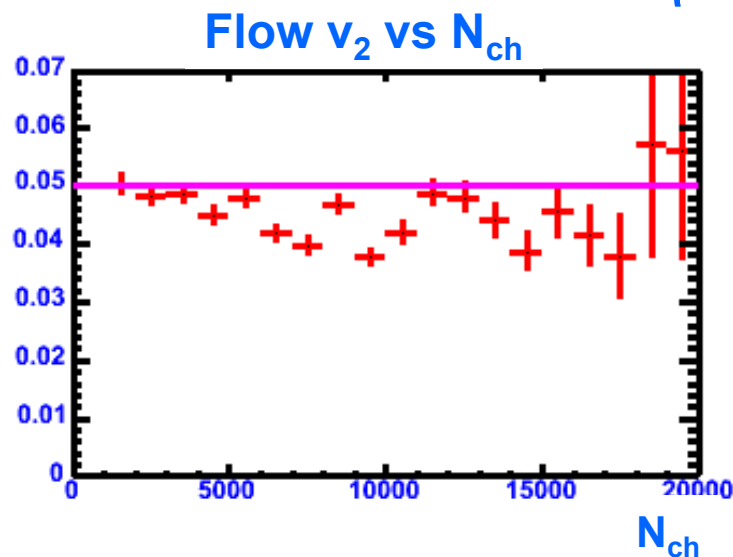
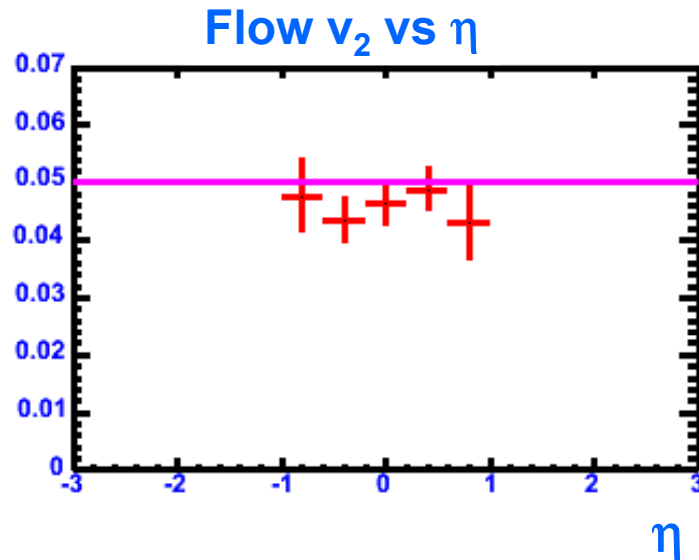


| Data Type | $\langle V_2(\psi_R) \rangle$ |
|-----------------------------|-------------------------------|
| Hit clusters, Pixel layer 1 | 0.042 |
| Hit clusters, Pixel layer 2 | 0.036 |
| Hit clusters, Pixel layer 3 | 0.032 |
| EM Barrel Calo | 0.029 |
| EM EndCap Calo | 0.031 |
| EM FCAL Calo | 0.036 |
| HAD FCAL Calo | 0.025 |

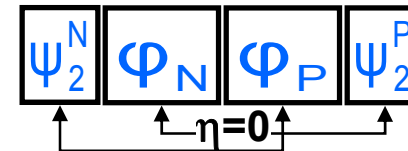
Correlation of signals with flow



Event Plane Method



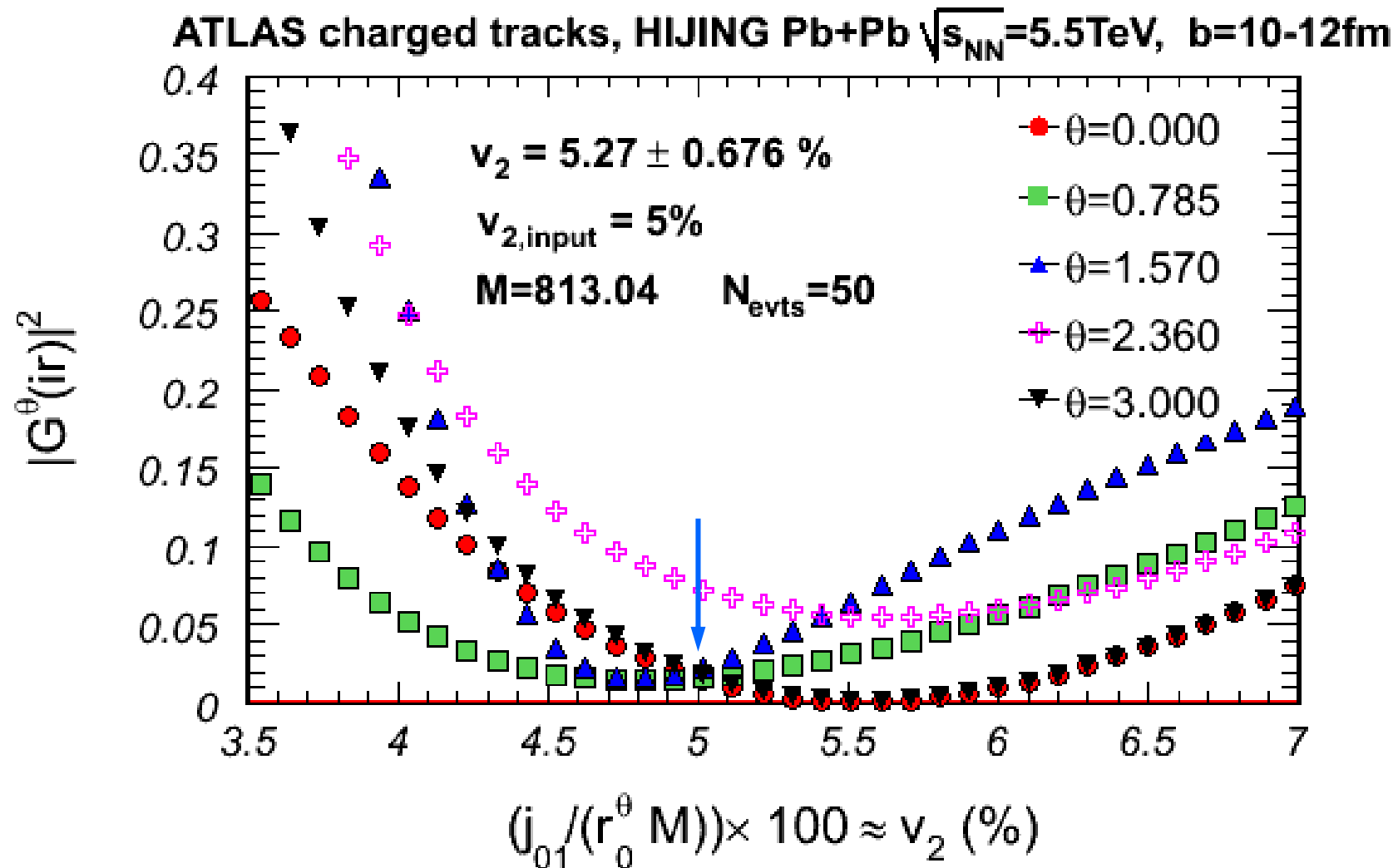
- Method: $v_2 = \langle \cos[2(\phi - \psi_R)] \rangle$
- Reaction plane estimated from flow



- Reconstructed flow is close to the **input 5% flow**
- Reconstructed v_2 **is flat against η , N_{ch}**
- Remaining difference (**$\sim 10\%$**) **is due to non - flow correlations** and will be accounted for by **MC corrections**



Lee-Yang-Zeroes Method

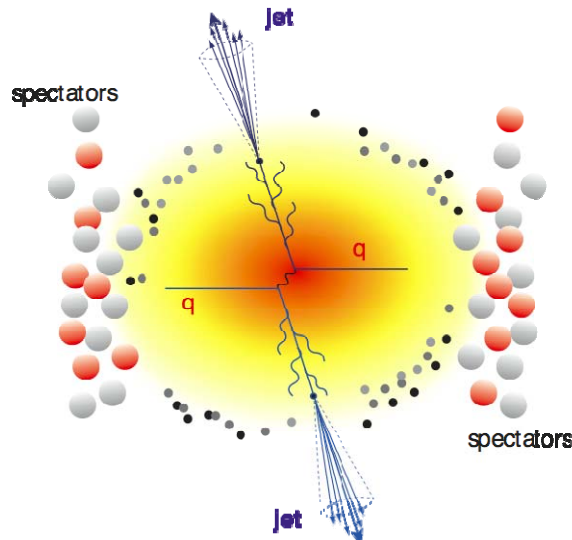




Jet Studies

Goal is to determine medium properties.

Jet quenching



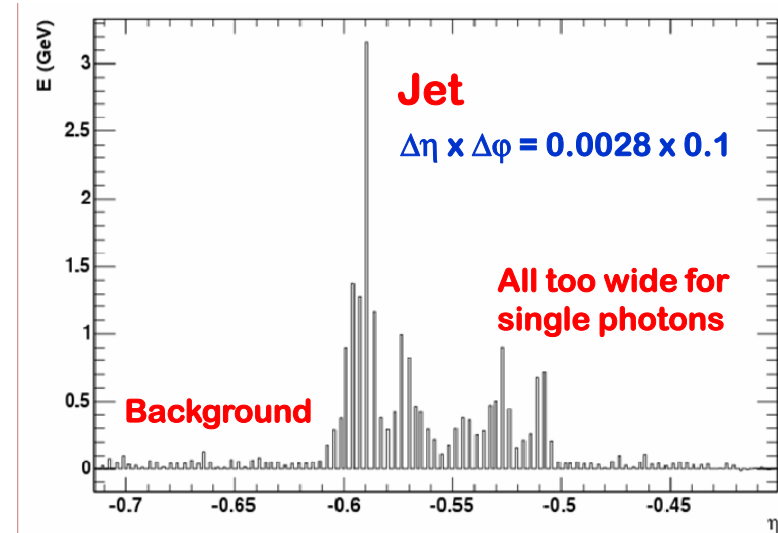
LHC: Copious hard radiation in high Q^2 final-state parton showers

- Both an opportunity and a challenge
 - Understanding jet quenching more difficult
 - Potentially: time-dependent probe of medium
- Resolving hard radiation in jets a must!

Fine segmentation of first EM sampling layer helps

Need to measure jet shapes:

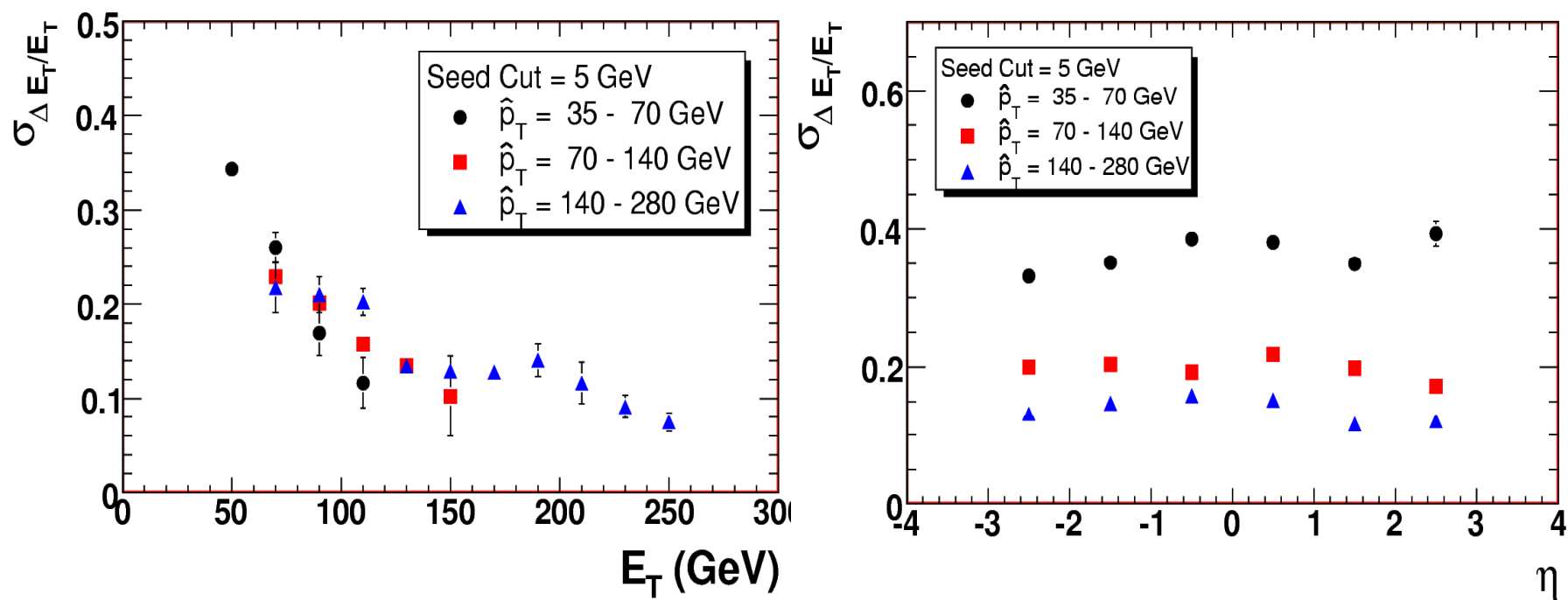
- Fragmentation function using tracking
- Core ET and jet profile using calorimeters
- Neutral leading hadrons using EM calorimeters





Jet Energy Resolution

Study of different event samples embedded
into central Pb+Pb HIJING (b=0-2 fm)

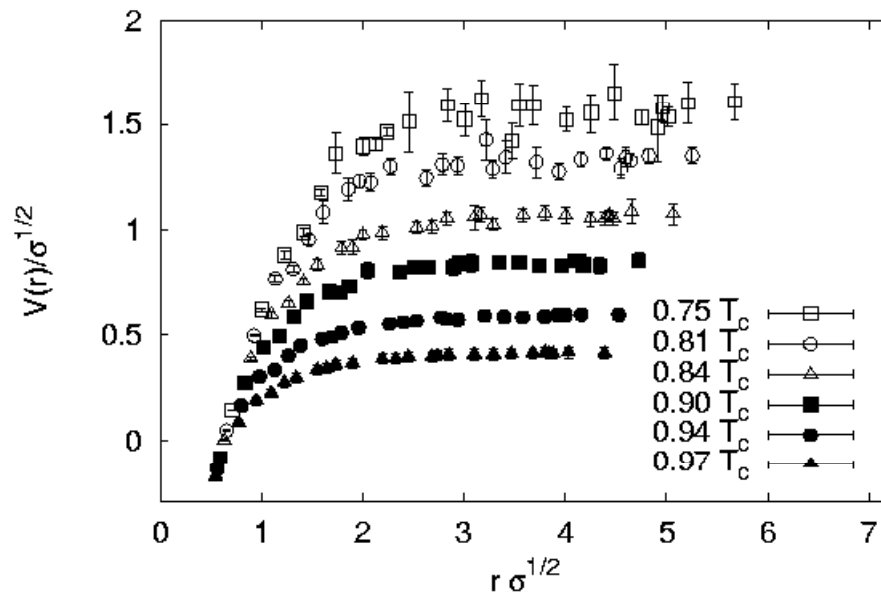


Results obtained using a standard pp cone algorithm
Another possibility is studied – Fast K_T Jet Finder



Quarkonia suppression

Color screening prevents various ψ , Υ , χ states to be formed when $T \rightarrow T_c$ to QGP (color screening length < size of resonance)



- Measurements of suppression patterns in production of heavy quarkonia states are an ideal thermometer for the plasma
- Important to separate $\Upsilon(1s)$ and $\Upsilon(2s)$ states!

| state | J/ψ | χ_c | ψ' | $\Upsilon(1s)$ | χ_b | $\Upsilon(2s)$ | χ_b' | $\Upsilon(3s)$ |
|------------|----------|----------|---------|----------------|----------|----------------|-----------|----------------|
| Mass [GeV] | 3,096 | 3,415 | 3,686 | 9,46 | 9,859 | 10,023 | 10,232 | 10,355 |
| B.E. [GeV] | 0,64 | 0,2 | 0,05 | 1,1 | 0,67 | 0,54 | 0,31 | 0,2 |
| T_d/T_c | 1.7-2.0 | 1.0-1.2 | 1.0-1.2 | ~5 | ~1.6 | ~1.4 | ~1.2 | ~1.3 |

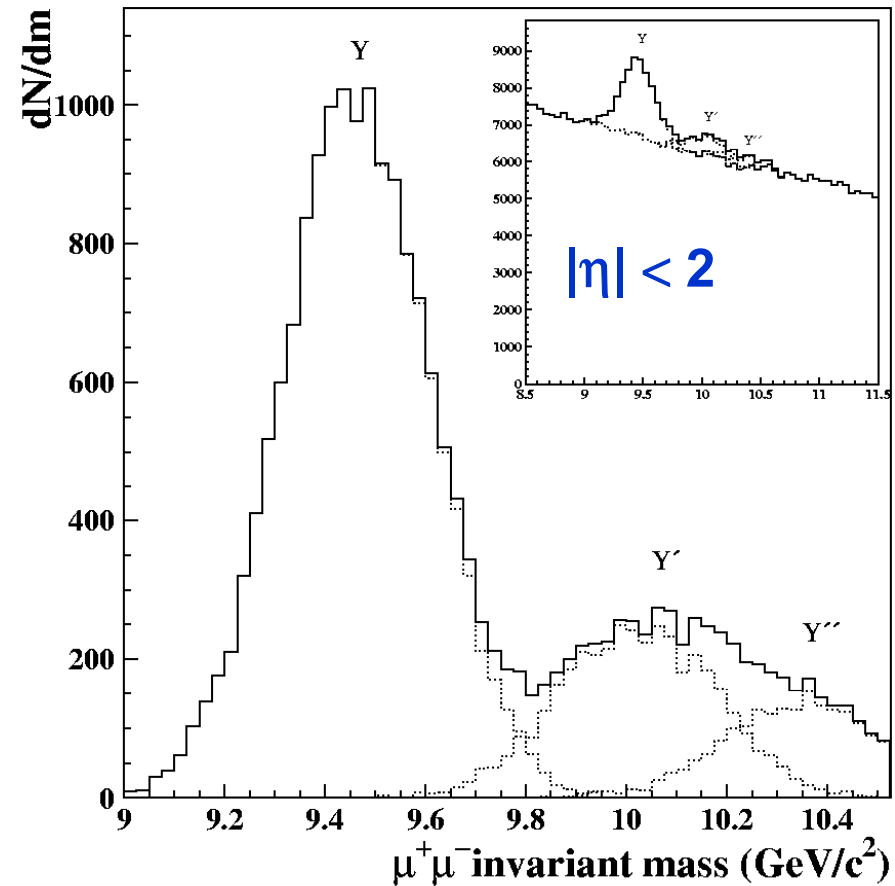


$\Upsilon \rightarrow \mu^+ \mu^-$ reconstruction

Low momentum muons measured by tagged ID tracks
Identified by coincidence with track segment in μ -spectrometer

| | $p_T^\mu > 3 \text{ GeV}$ | | |
|-------------------------|---------------------------|--------------|----------------|
| | $ \eta < 1$ | $ \eta < 2$ | $ \eta < 2.5$ |
| Acceptance + efficiency | 4.7% | 12.5% | 17.5% |
| Resolution | 123 MeV | 145 MeV | 159 MeV |
| S/B | 0.3 | 0.2 | 0.2 |
| $S/\sqrt{S+B}$ | 37 | 46 | 55 |
| Rate/month | 5,700 | 15,000 | 21,200 |

For $|\eta| < 2$ (12.5% acc+eff) we expect
15K Υ /month of 10^6 s at $L=4 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$





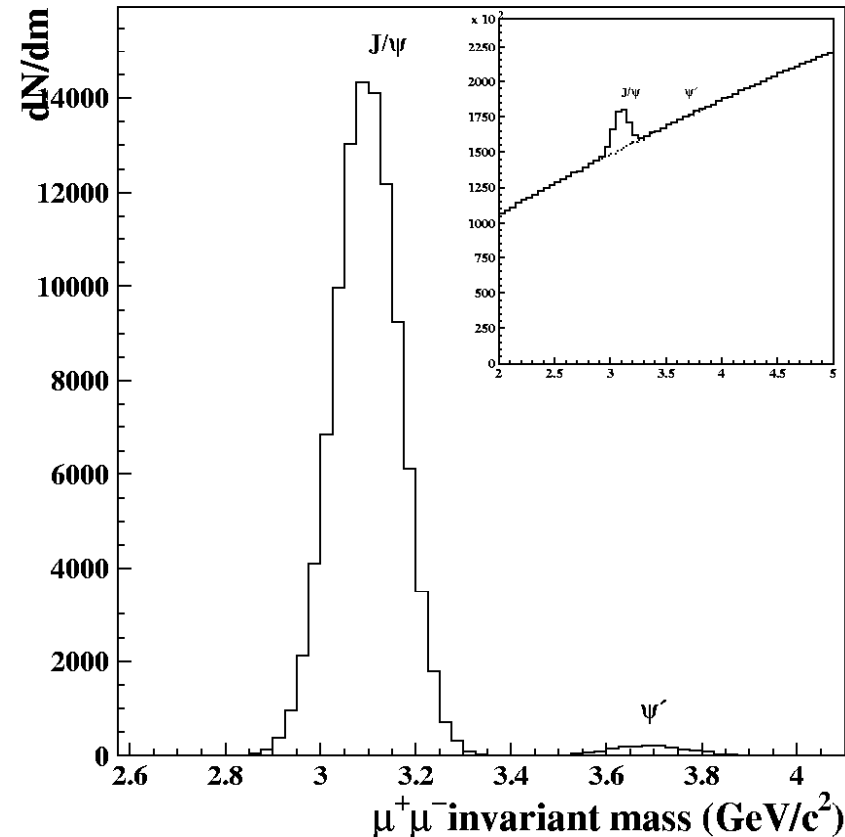
$J/\psi \rightarrow \mu^+ \mu^-$ reconstruction

$|\eta| < 2.5, p_T^\mu > 1.5 \text{ GeV}$

| | $ \eta < 2.5$ | |
|-------------------------|---------------------------|-----------------------------|
| | $p_T^\mu > 3 \text{ GeV}$ | $p_T^\mu > 1.5 \text{ GeV}$ |
| Acceptance + efficiency | 0.055% | 0.530% |
| Resolution | 68 MeV | 68 MeV |
| S/B | 0.4 | 0.15 |
| $S/\sqrt{S+B}$ | 56 | 113 |
| Rate/month | 11,000 | 104,000 |

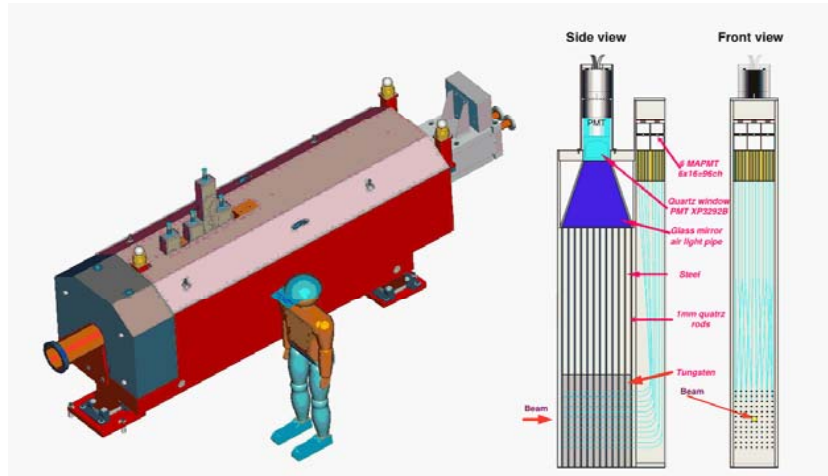
We expect 8K to 100K $J/\psi \rightarrow \mu^+ \mu^-$ per month of 10^6 s at $L=4 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$

A trigger with muon $p_T > 1.5 \text{ GeV}$ is more efficient if torroidal field is reduced for HI runs. The mass resolution is 15% worse but we gain a factor 2-3 in statistics

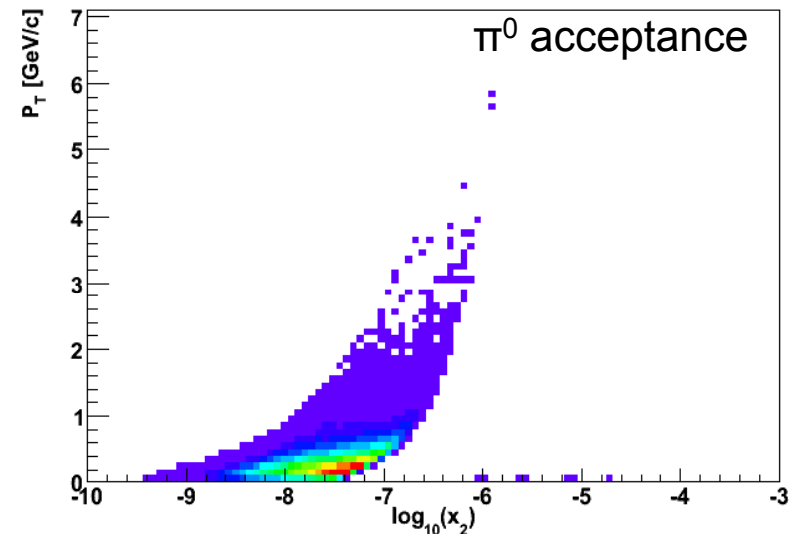
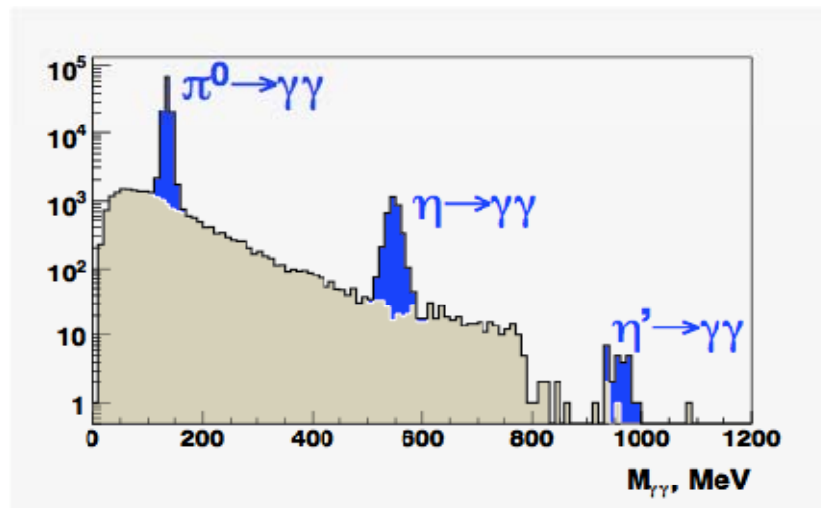




Low-x Physics with ZDC



- ZDC will be used for centrality and **Ultrapерipheral ($\gamma\text{-}\gamma$ and $\gamma\text{-nucleon}$) Pb+Pb collisions**
- ZDC reconstructs also neutral particles at very high rapidities: **physics processes at very low x, e.g. Color Glass Condensate**





Summary

- ATLAS Heavy Ion physics program addresses primary physics questions of interest at the LHC
- **Global observables**, including elliptic flow, should be accessible from day-one, even with a very low luminosity (early scheme)
- **Jet physics** is very promising with Atlas unique capabilities of measuring isolated direct photons, separating jets from heavy ion background, measuring jet shapes, hard radiation components
- **Z+jet, γ +jet, jet-jet** correlations
- **Heavy-quarkonia physics** with capability to measure and separate Υ and Υ' , J/ψ using a specially developed μ tagging method
- **Low-x physics** & Ultra-peripheral collisions
- **Heavy quarks** (esp. b physics)

BACKUPS

Summary of Ions

The desired species for a systematic HI study are as follow

| Collision | R (fm) | Luminosity (cm ⁻² s ⁻¹) | dN _{ch} /dy (maximum) | Interaction rate |
|--------------------------------------|-----------|---|-----------------------------------|---------------------|
| p+p | ~1 | 1x10 ³⁴ | <250 | 1 GHz |
| ²⁰⁸ Pb+ ²⁰⁸ Pb | 7.1 | 1x10 ²⁷ | <8000 | 8 kHz |
| ⁴⁰ Ar+ ⁴⁰ Ar | 4.1 | 6x10 ²⁸ | <800 | 200 kHz |
| p+ ²⁰⁸ Pb | | 1x10 ³⁰ | <150 | 2 MHz |
| p+ ⁴⁰ Ar | | 1x10 ³¹ | <120 | 6 MHz |

In addition different colliding energies would provide for the study of different energy densities.

| Ion | Mass | dN/dy | R (fm) | Luminosity |
|---------|------|--------|--------|----------------------|
| Pb | 208 | <8,000 | 7.1 | 10^{27} |
| Sn | 120 | | 5.9 | 1.7×10^{28} |
| Kr | 84 | <900 | 5.3 | 6.6×10^{28} |
| Ar | 40 | <800 | 4.1 | 10^{30} |
| O | 16 | | 3.0 | 10^{29} |
| p+Pb,Ar | | <200 | | 10^{31} |
| d+Pb,Ar | | | | 10^{31} |
| p+p | | 250 | | 10^{34} |

Beam Energy: 2.75 and 1.00 TeV/nucleon

Calorimeters Granularity

- ATLAS calorimeters covers a large pseudo-rapidity range $|\eta| < 5.0$
- Both EM and Hadronic calorimeters are segmented longitudinally in several compartments.
- The first section of the EM calorimeter is finely segmented in eta strips.

EM Barrel and Endcap

| | |
|---|----------------|
| Coverage | $ \eta < 3.2$ |
| Segmentation Long. | 3 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 1 | 0.003x0.1 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 2 | 0.025x0.025 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 3 | 0.05x0.25 |

Hadronic Tile

| | |
|---|----------------|
| Coverage | $ \eta < 1.7$ |
| Segmentation Long. | 3 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 1 | 0.1x0.1 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 2 | 0.1x0.1 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 3 | 0.2x0.1 |

Hadronic LAr

| | |
|---|--------------------|
| Coverage | $1.5 < \eta < 3.2$ |
| Segmentation Long. | 4 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 1 | 0.1x0.1 |
| Segmentation ($\Delta\eta \times \Delta\phi$) 2 | 0.2x0.2 |

Forward Calorimeter

| | |
|---|--------------------|
| Coverage | $3.1 < \eta < 4.9$ |
| Segmentation Long. | 4 |
| Segmentation ($\Delta\eta \times \Delta\phi$) (all) | 0.2x0.2 |

Examples of Calorimeter Performance

| | |
|---|--|
| Electromagnetic Energy Resolution | $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.3\%$ |
| EM Angular Resolution | $\sigma_\theta = \frac{60\text{mrad}}{\sqrt{E}}$ |
| EM Timing Resolution | $\sigma_\tau = \frac{4}{E} \text{ns} \cdot \text{GeV}$ |
| Hadronic Calorimeter Energy Resolution | $\frac{\sigma_E}{E}(\pi) = \frac{50\%}{\sqrt{E}} \oplus 3\%$ |

The above performance was achieved with test beam modules



Detector Occupancies

$b = 0 - 1\text{fm}$

Si detectors:

Pixels $< 2\%$

SCT $< 20\%$

TRT:

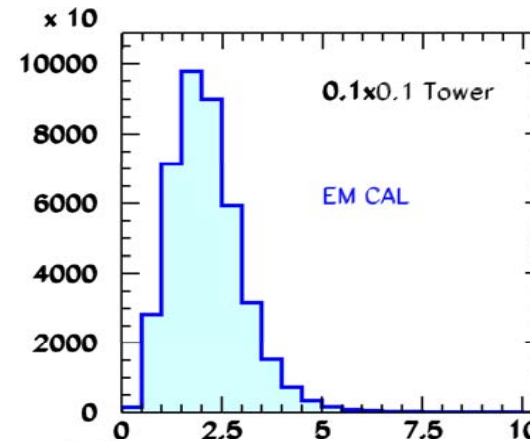
too high, unusable

(limited usage for PbPb collisions is under investigation)

Muon Chambers:

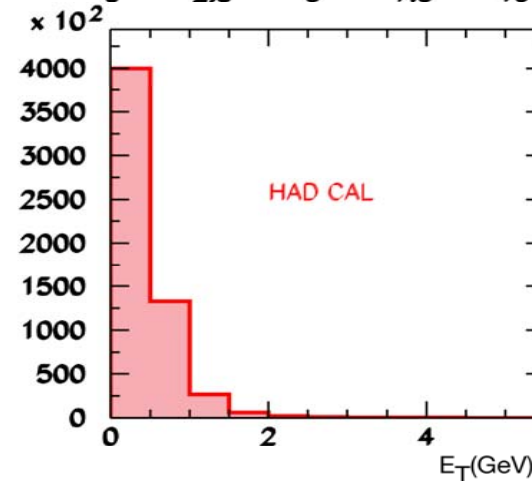
0.3 – 0.9 hits/chamber
(\ll pp at $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)

Calorimeters ($|\eta| < 3.2$)



On average:

$\sim 2 \text{ GeV/Tower}$



$\sim .3 \text{ GeV/Tower}$

Track Reconstruction

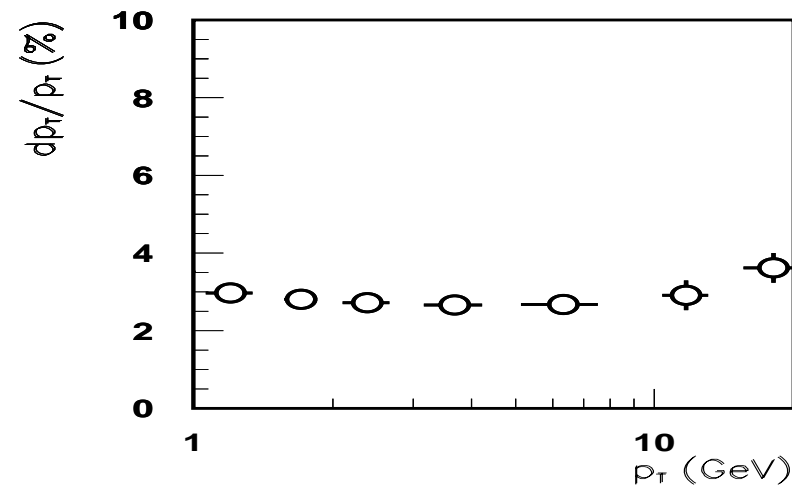
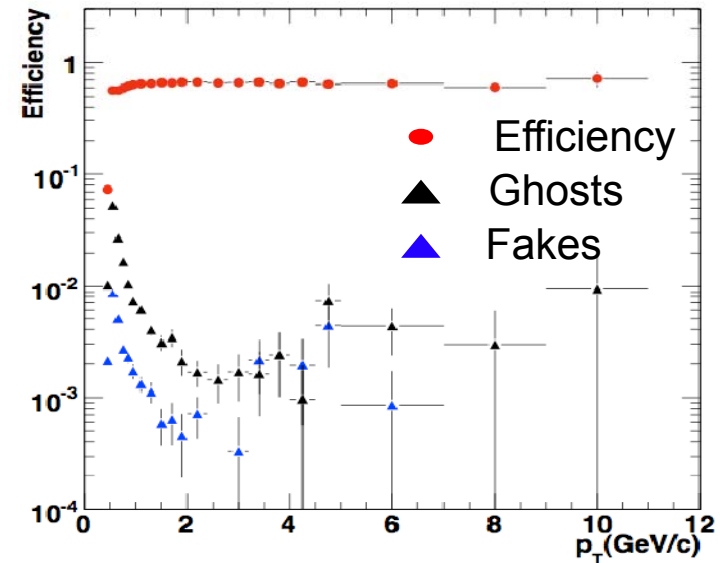
- Pixel and SCT detectors
- Threshold $p_T > 1$ GeV
- Tracking cuts:
 - At least 10 hits out of 11(13) available in the barrel (end-caps)
 - All three pixel hits
 - At most 1 shared hits
 - $\chi^2/\text{dof} > 4$

For p_T : 1 - 10 GeV/c:

efficiency ~ 70 %

fake rate < 1 %

Momentum resolution ~ 3 %
(2% - barrel, 4-5% end-caps)

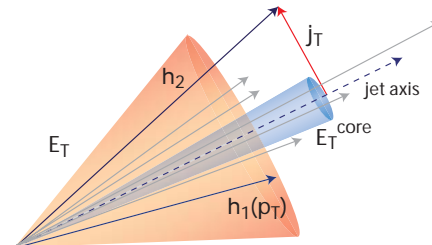
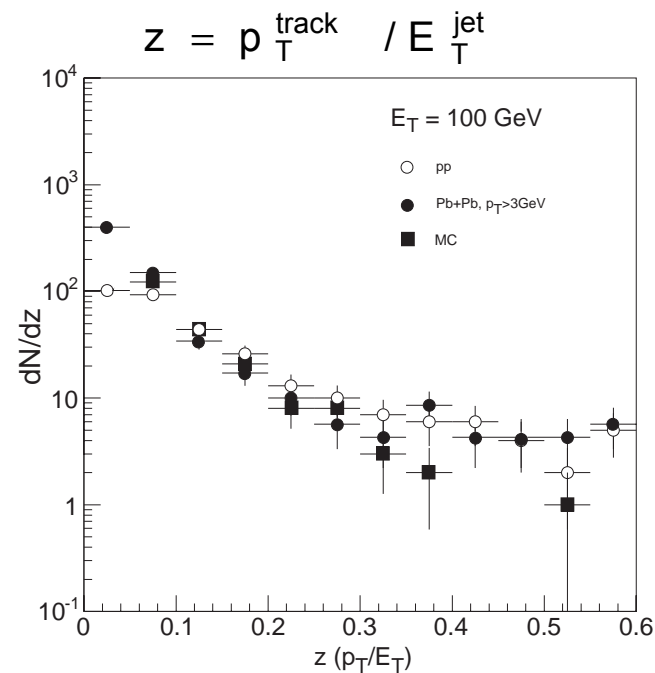




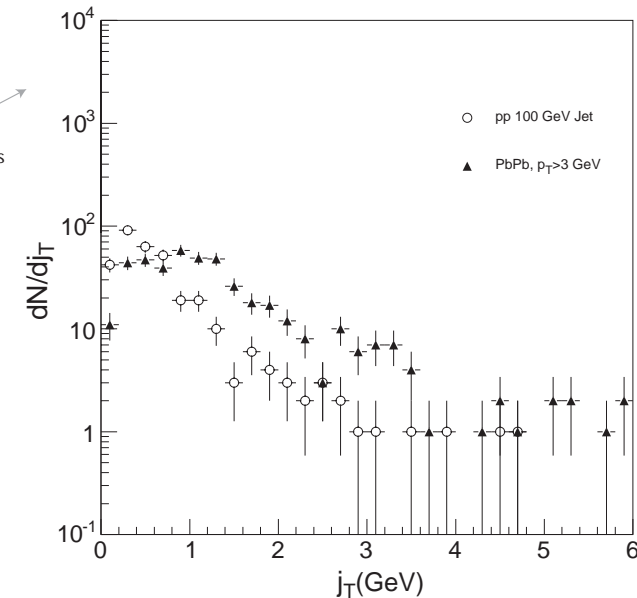
Jet Studies with Tracks

- Jets with $E_T = 100$ GeV
- Track $p_T > 3$ GeV

Fragmentation function



Momentum component perpendicular to jet axis



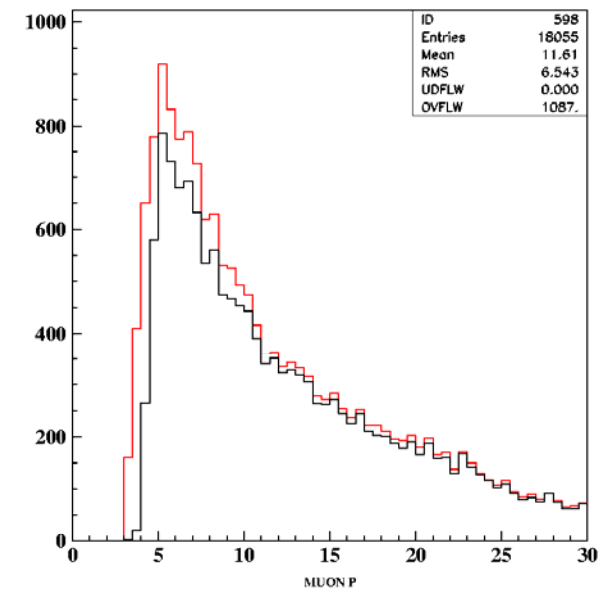
PbPb \approx HIJING-unquenched \approx pp

**dN/dj_T broader in PbPb than in pp
(background fluctuations)**



How to measure μ ?

- **Global method (A):** use tracks **fully traversing** the μ -spectrometer, which allows momentum measurement in the standalone μ -spectrometer, then associate with ID tracks through a **global fit**.
 - **Tagging method (B):** select ID tracks whose extrapolation coincide with a **track segment** in the μ -spectrometer.
- Advantage of A over B: better p measurement (**true for Z^0 , not J/ψ , Υ**), better purity.
- Advantage of B over A: lower p threshold **=> better acceptance (3 instead of 4 GeV)**.
- For this study, A+B are used, with a priority to method A when possible. Selection of pairs with at least one μ from method A.



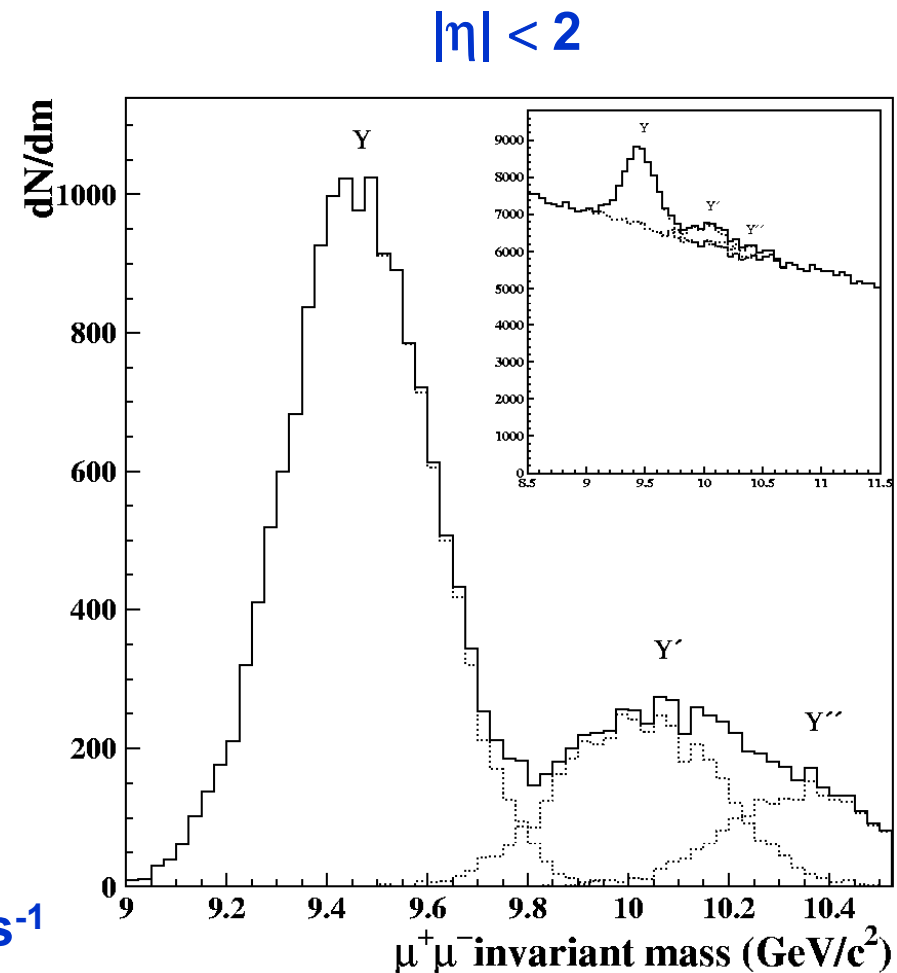


$\Upsilon \rightarrow \mu^+ \mu^-$ reconstruction

| Global fit Global+tag | $p_T^\mu > 3 \text{ GeV}$ | | |
|----------------------------|---------------------------|------------------|----------------|
| | $ \eta < 1$ | $ \eta < 2$ | $ \eta < 2.5$ |
| Acceptance + efficiency | 2.6% 4.7% | 8.1% 12.5% | 12.0% 17.5% |
| Resolution | 123 MeV | 145 MeV | 159 MeV |
| S/B | 0.4 0.3 | 0.3 0.2 | 0.3 0.2 |
| $S/\sqrt{S+B}$ | 31 37 | 45 46 | 55 55 |
| Rate/month | | 10,000 15,000 | |

For $|\eta| < 2$ (12.5% acc+eff) we expect
15K Υ /month of 10^6 s at $L=4 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$

A di-muon trigger study is under way





$J/\psi \rightarrow \mu^+ \mu^-$ reconstruction

| Global fit Global+tag | $ \eta < 2.5$ | |
|----------------------------|---------------------------|-----------------------------|
| | $p_T^\mu > 3 \text{ GeV}$ | $p_T^\mu > 1.5 \text{ GeV}$ |
| Acceptance + efficiency | 0.039% 0.055% | 0.151% 0.530% |
| Resolution | 68 MeV | 68 MeV |
| S/B | 0.5 0.4 | 0.2 0.15 |
| $S/\sqrt{S+B}$ | 52 56 | 72 113 |
| Rate/month | 8,000 11,000 | 30,000 104,000 |

We expect 8K to 100K $J/\psi \rightarrow \mu^+ \mu^-$
per month of 10^6 s at $L=4 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$

If a trigger is possible forward with a muon $p_T > 1.5 \text{ GeV}$, we gain a factor 4
in statistics...A solution might be to reduce the toroidal field for HI runs

$|\eta| < 2.5, p_T^\mu > 1.5 \text{ GeV}$

